別記様式第５号

論文審査の要旨

博士の専攻分野の名称	博　士　（　工学　）	氏名	DU XINRU
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論　文　題　目

Study on Energy Harvesting from Wave and Flow Energy Using Triboelectric Generator and Piezoelectric Generator

（摩擦発電と圧電発電を用いた波・流れエネルギーによるエネルギーハーベスティング技術に関する研究）

論文審査担当者

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〔論文審査の要旨〕

The energy crisis has a significant impact on the economy, politics, and environment of both developed and developing countries. Therefore, utilization of renewable energy is one of the most promising methods to deal with the energy crisis. Considering the reliable, robust, and desirable characteristics of ocean energy, utilizing of it is one promising method. Among it, ocean wave and flow energy are ubiquitous. The aim of the thesis is to propose suitable wave and flow energy harvesting devices for isolated islands, sensors on fish aggregating device (FAD), and wave information monitoring for various weather environment and low-frequency wave conditions.

In Chapter 2, to facilitate continuous and stable energy supply based on PENGs (Piezoelectric Nanogenerators) / TENGs(Triboelectric Nanogenerators) for both FAD equipment and islands, we design a flexible piezoelectric device (FPED) based on PENGs used for ocean energy harvesting. Our approach involves the development of FPEDs coated with piezoelectric paint spray technology. Simultaneously, hemi-spherically spring origami triboelectric nanogenerators (HSO-TENGs) designed for self-powered ocean wave monitoring are developed based on TENGs technology.

In Chapter 3, FPEDs are attached to the frame of a FAD to assess their performance characteristics in varying submerged depths and support types. Through examination under various wave conditions, we've identified the key parameters significantly impacting electrical performance. The maximum output voltage can be increased obviously with cantilever support, fully submerged depths, thickness 50 μm, and aspect ratio 1:2. Utilizing the experimental setup as a basis, we construct a theoretical model and further refine a computational model employing the immersed boundary method to analyze FPED-wave interactions. The latter is found to be a better predictor of power generation from FPEDs than the former. In addition, a field test conducted in real sea conditions, supported by a remote data monitoring system for the painted FPEDs, demonstrate exceptional performance even under extreme bending, weathering, and fatigue.

In Chapter 4, HSO-TENGs are designed for self-powered ocean wave monitoring, driven by two optimization approaches. (1) Swing machine experiments are employed to assess the HSO-TENGs' monitoring capabilities concerning wave height and period, showing satisfactory accuracy. Three structural parameters, the weight of magnet mass, the height of the hammer, and the length of the external swing arm, are found to increase average voltage generation by 33%, 62%, and 50%. (2) Numerical simulations utilizing the smoothed particle hydrodynamics (SPH) method can find the most suitable fixed condition for HSO-TENGs to effectively sense wave changes. Then, no-submergence that can fully compress and stretch SO-TENGs is selected from three fixed conditions. Subsequent wave tank experiments aim to evaluate their proficiency in detecting wave height, period, frequency, and direction. The maximum voltage can reach 15v. When the four springs origami triboelectric nanogenerators (SO-TENGs) are connected in parallel, the output voltage can supply the temperature and humidity sensor continually. Finally, we investigate the HSO-TENG's ability to monitor wave direction and spreading parameters through numerical SPH circular wave tank simulations. And the SPH method is found to simulate the motion of HSO-TENG and similar energy harvesting devices in waves well, thereby guiding device design and predicting device performance.

In Chapter 5, we develop a novel numerical model to control turbulent flow filed and drag reduction performance with polymer coating. This model merges mesoscopic methods with computational fluid dynamics (CFD) techniques, addressing the underexplored area of non-uniform polymer drag reduction in external flows. This model integrates direct numerical simulation (DNS) and large eddy simulation (LES) methods within the CFD framework. Both of them are in good agreement with the previous reference results, which proves the reliability of the model, Our approach initially couples the mesoscopic dissipative particle dynamics (DPD) method with DNS and LES methods, validating the results through the finitely extensible nonlinear elastic approach. Subsequently, we utilize the model to discuss the impact of varying polymer region heights on non-uniform polymer drag reduction. Particularly noteworthy is the efficiency highlighted by the LES method, offering computational efficiency, especially at higher Reynolds numbers. Then, the mean velocity, the root-mean-square velocity fluctuations and the Reynolds shear stress presents a monotonous trend to the particle energy density. Furthermore, releasing polymer particles close to the wall is also found to achieve drag reduction, and the drag reduction efficiency of releasing polymer particles in half of the region is very high. The new vortex grows again above the polymer region. Our model illuminates that significant polymer drag reduction efficiency persists even when the polymer region doesn't span the entire fluid area, as observed in conditions like the application of polymer coatings. And high energy dissipation gradually changes from dispersion to concentration during the process of the drag reduction. Lastly, for different Reynolds numbers, the model can be widely used and has a good prospect.

In the chapter 6, conclusions and future works are summarized. Firstly, we introduced the structures and components of two kinds of wave and flow energy harvesters based on PENG and TENG. Their key parameters are investigated under varied wave conditions. The electrical power of them can be provided to nearby island residents and sensors on FAD, or wave information monitoring. Secondly, from the fluid simulation of polymer molecules, to the fluid-solid coupling of rigid bodies with complex mechanical structures, to the fluid-solid coupling of flexible bodies, various numerical algorithms that combine the Lagrangian method and the Euler method help improve calculation efficiency and avoid grid distortion. Thirdly, to improve flow energy harvesting, one numerical simulation method of flow control, DNS/LES-DPD, is proposed to simulate polymer distribution impacting turbulent distribution on surfaces, applicable in marine contexts like pipelines, vehicles, and submarines without structural change of wall and cylinder. Then in the future works, the devices based on TENG and PENG should continually focus on real-sea area tests for at least a year to validate the reliability of the devices and the accuracy of the numerical model. The estimated algorithms of electric power will be further refined and developed to enhance accuracy and reliability. Based on the DNS/LES-DPD method, the specific relationship between polymer coating distribution, turbulence field, and PENG/TENG power generation performance will be explored. The flow control numerical method, DNS/LES-DPD method, should focus on cases with higher Reynolds number.

With the above evidence, the applicant is judged as sufficiently qualified to be awarded the degree of Doctor of Philosophy in Engineering.

備考：審査の要旨は，1,500 字以内とする。